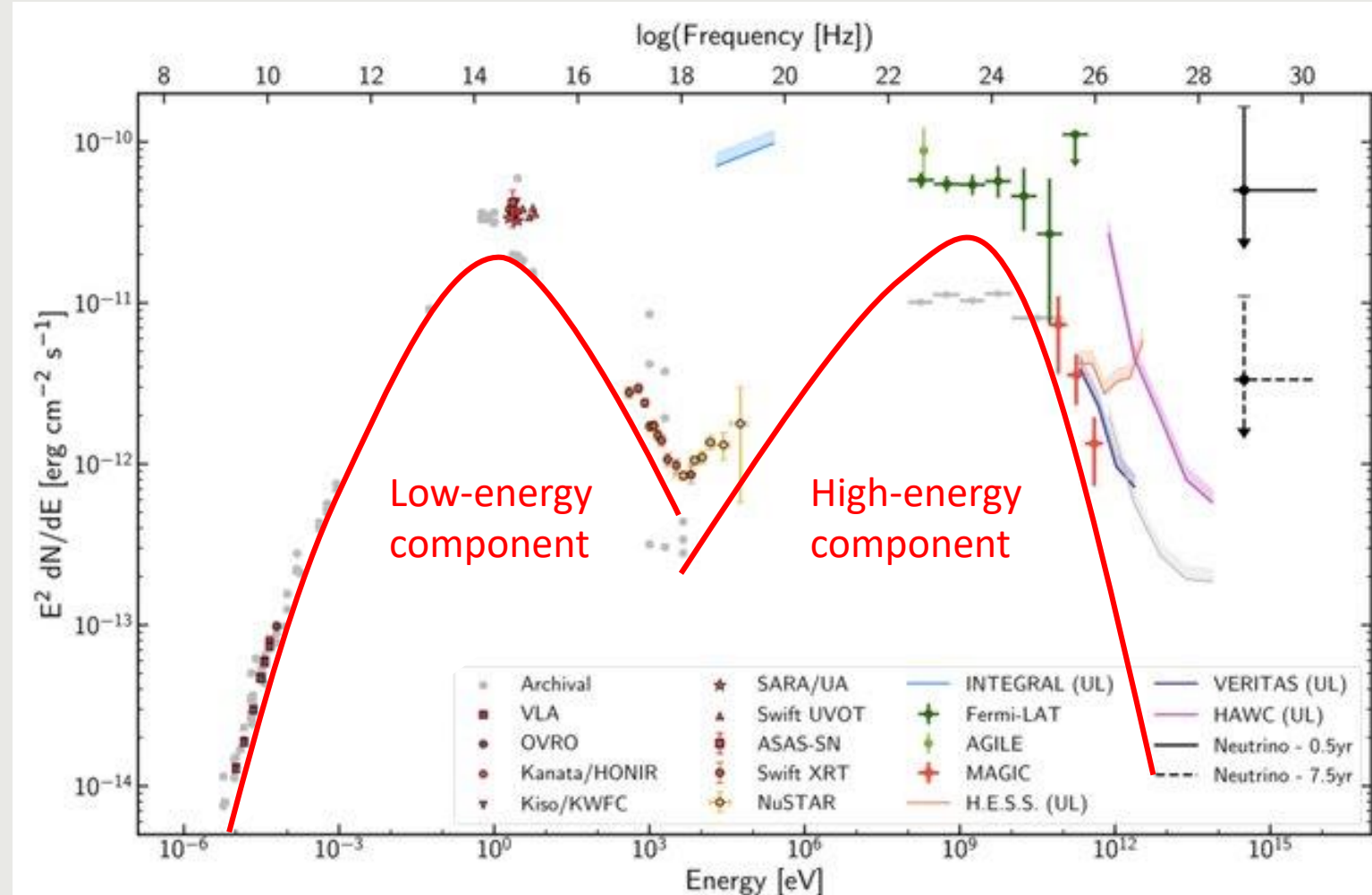


High-Energy Polarimetry as a Probe into Cosmic Ray Acceleration and Neutrino Production in Jets

Haocheng Zhang (NPP Fellow/NASA GSFC)



A Multi-Messenger View of Blazars



[IceCube 2018 Science 361, 1387](#)

- ❑ What is the physical connection between neutrinos and multi-wavelength flares?
- ❑ How do blazar jets accelerate cosmic rays?
- ❑ Can blazars produce ultra-high-energy cosmic rays?

Key unknowns:

1. Leptonic vs hadronic
2. Particle acceleration mechanism
3. Physical conditions in the blazar zone

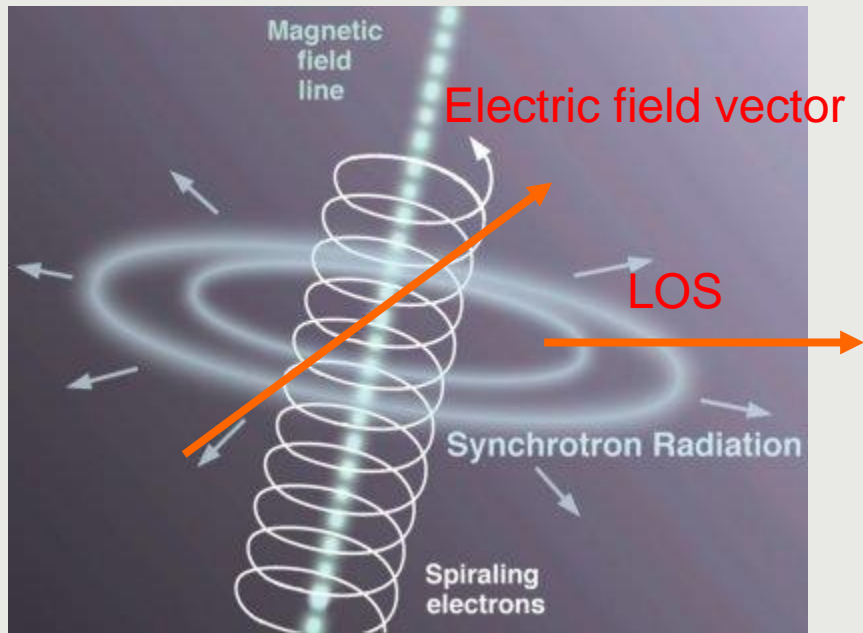
Current models encounter serious troubles in explaining the multi-wavelength emission and the neutrino event.

The Power of High-Energy Polarimetry

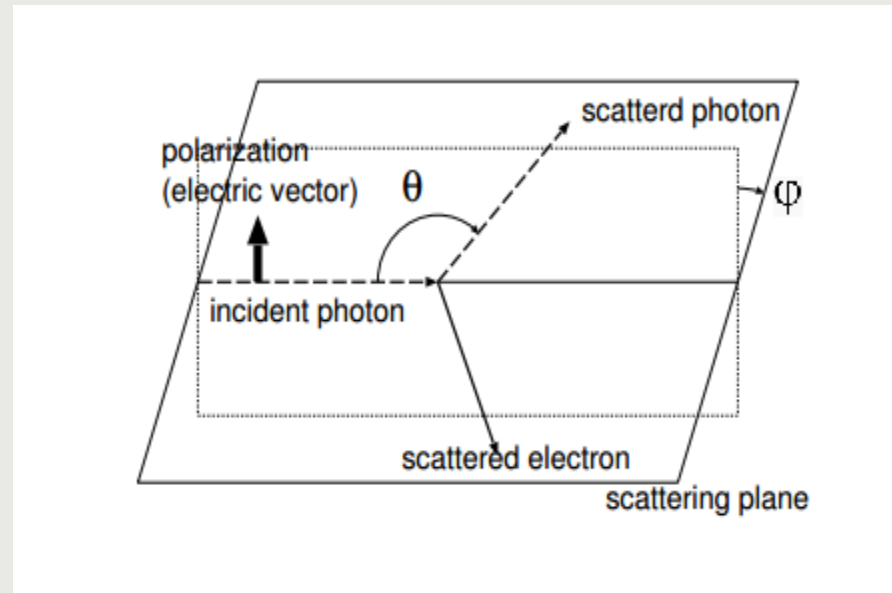
We need high-energy polarimetry:

1. Intrinsic property of photons
2. Unambiguous signature of neutrino production
3. Unique to X-ray polarimetry—distinguish particle acceleration mechanisms
4. Unique to MeV polarimetry—detect proton synchrotron and ultra-high-energy cosmic rays

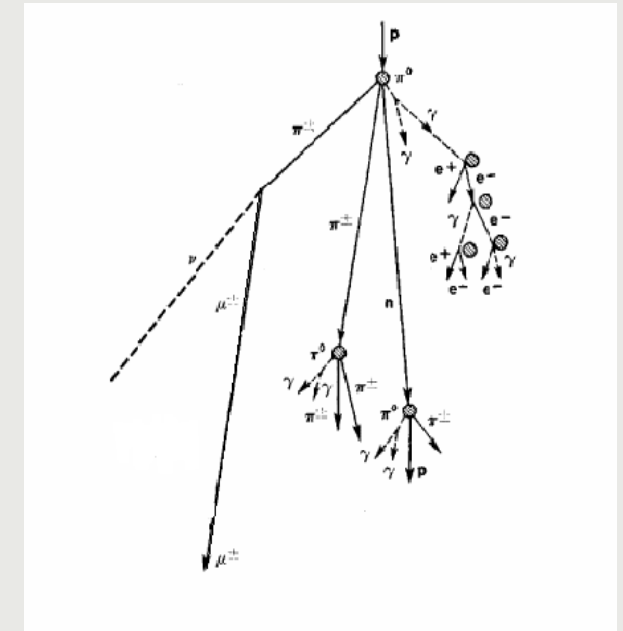
Synchrotron & Compton Scattering



Synchrotron is strongly polarized.



Compton scattering reduces polarization.



Protons and cascading charged particles can emit via synchrotron.

1. Pure leptonic: SSC and/or EC
2. Leptonic + hadronic cascades: SSC and/or EC + pair synchrotron
3. Proton synchrotron: SSC + pair/proton synchrotron

High-energy polarization degree can distinguish these models!

Hadronic Cascade

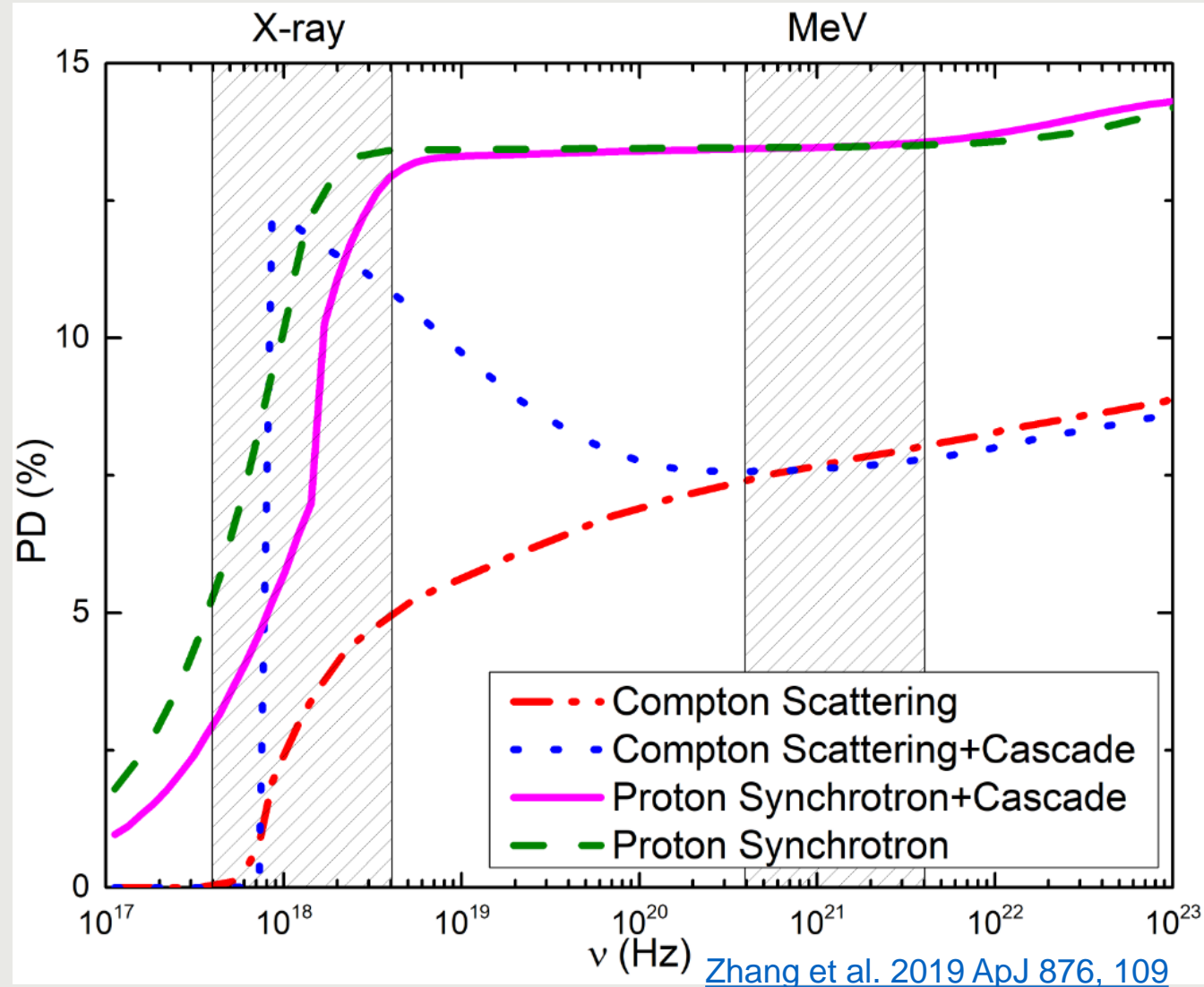
$$p + \gamma \rightarrow p(n) + \pi^0(\pi^+)$$

$$p + \gamma \rightarrow p + e^+ + e^-$$

$$\pi^0 \rightarrow \gamma + \gamma, \quad \pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_\mu + \nu_e$$

Leptonic vs Hadronic



1. Hadronic models predict systematically higher polarization degrees in X-ray and MeV gamma-ray bands.
2. High X-ray polarization degree uniquely points to neutrino production, if the X-ray emission is in the high-energy spectral component.
3. High MeV polarization degree points to proton synchrotron, which can constrain the maximal proton energy.

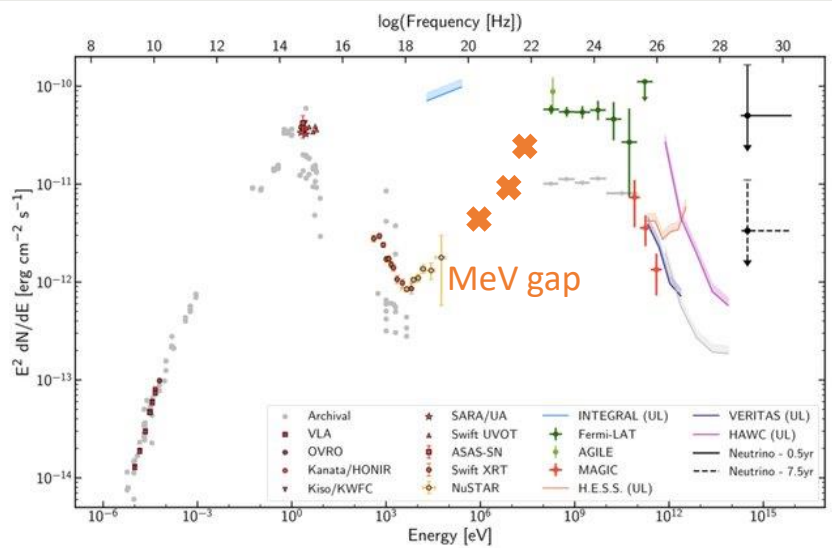
Results do not depend on free parameters in spectral modeling

Detectable? Yes!

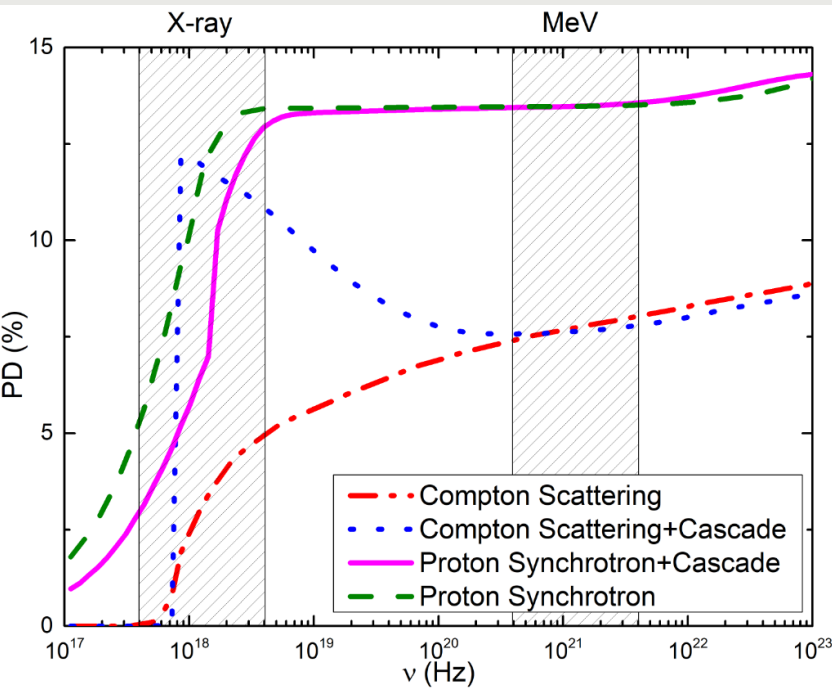
2FHL Name	Optical Pol. (%)	lep. Pol. (1 keV, %)	had. Pol. (1 keV, %)	lep. Pol. (1 MeV, %)	had. Pol. (1 MeV, %)
(1)	(2)	(4)	(5)	(6)	(7)
J0456.9–2323	9.9*	4.2	9.5	1.0	10.1
J0957.6+5523	5.7 [†]	1.6	6.6	1.0	7.2
J1224.7+2124	5.4*	1.8	50.8	0.0	55.3
J1256.2–0548	15.0*	8.7	14.4	1.6	16.4
J1427.3–4204	...	...	...	...	...
J1512.7–0906	3.8*	2.5	9.7	0.0	9.7
J2000.9–1749	13.0 [†]	6.0	13.4	0.5	15.7
J2254.0+1613	5.8*	1.9	6.2	0.0	6.9
J0456.9–2323	35.3*	15.3	34.7	3.6	38.3
J0957.6+5523	...	...	...	...	...
J1224.7+2124	29.1*	1.8	50.8	0.0	55.3
J1256.2–0548	34.5*	20.1	33.1	3.7	37.9
J1427.3–4204	...	...	...	...	...
J1512.7–0906	25.8*	17.1	66.4	0.1	66.6
J2000.9–1749	...	...	...	...	...
J2254.0+1613	25.0*	8.7	28.0	0.2	28.4

1. Leptonic X-ray and MeV gamma-ray polarization degrees are too low to observe by current missions.
2. Hadronic X-ray and MeV gamma-ray polarization degrees are detectable by IXPE and COSI, if the blazar is bright.

Multi-Wavelength Spectropolarimetry & Neutrino Detection



keV	MeV	ν	Conclusion
Y	Y	Y	Proton synchrotron, ν , UHECR (?)
N	Y	Y	Proton synchrotron, ν , UHECR (?)
Y	N	Y	Leptonic+hadronic cascades, ν , CR
Y/N	Y/N	N	Unknown mechanism (unlikely) or we need a better IceCube
N	N	Y	ν is not from the blazar zone
N	N	N	Pure leptonic



Scientific potentials:

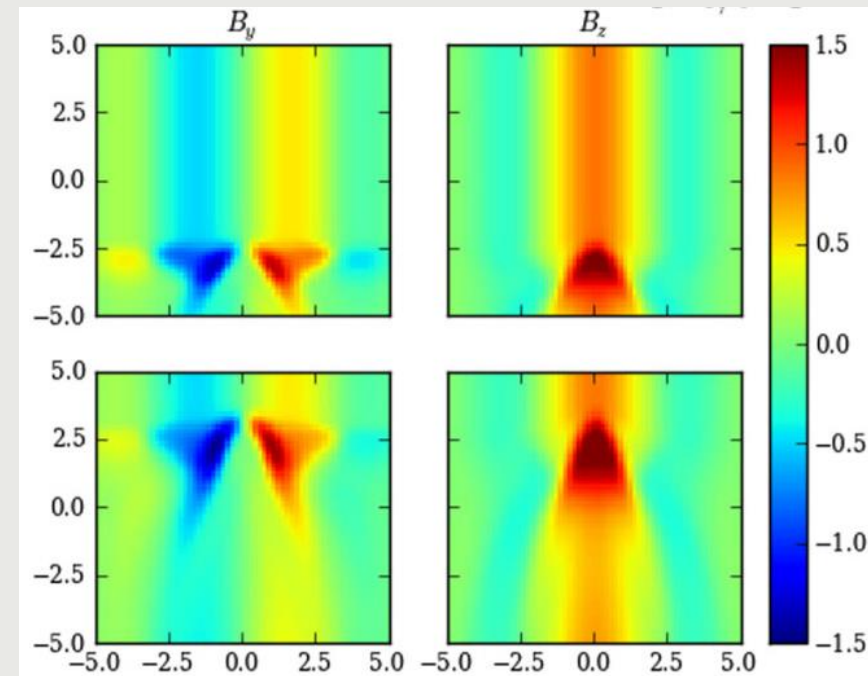
We can fully understand the connection between neutrinos and multi-wavelength emission, and potentially find the source of ultra-high-energy cosmic rays!

Difficulties:

IXPE and COSI are SMEX, may not fully answer above questions. We need MIDEX or Probe missions to address these issues.

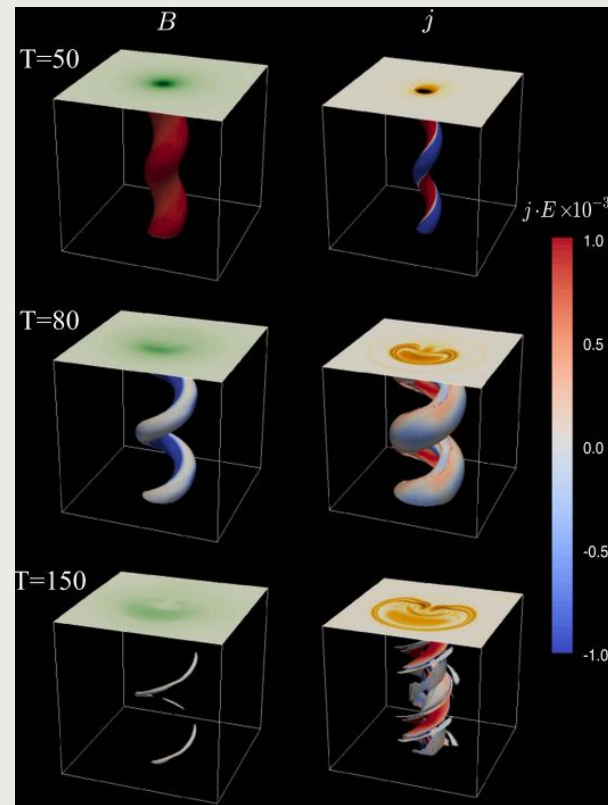
Particle Acceleration & Blazar Zone Dynamics

Shock



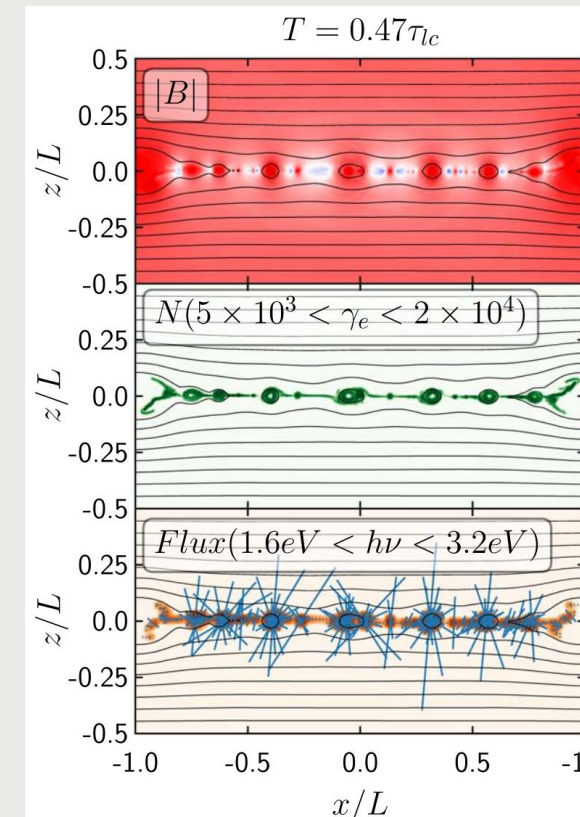
[Zhang et al. 2016 ApJ 817, 63](#)

Kink



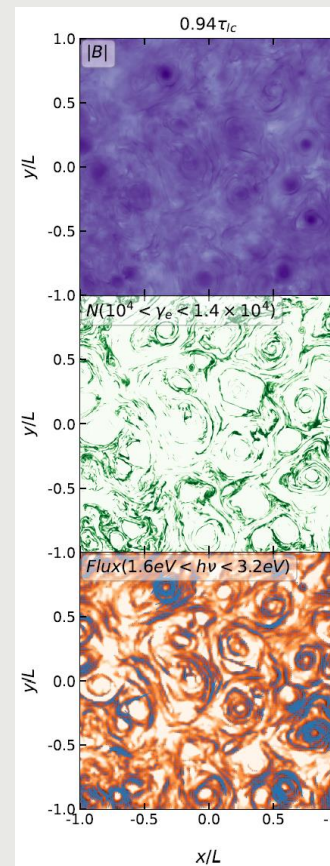
[Zhang et al. 2017 ApJ 835, 125](#)

Reconnection



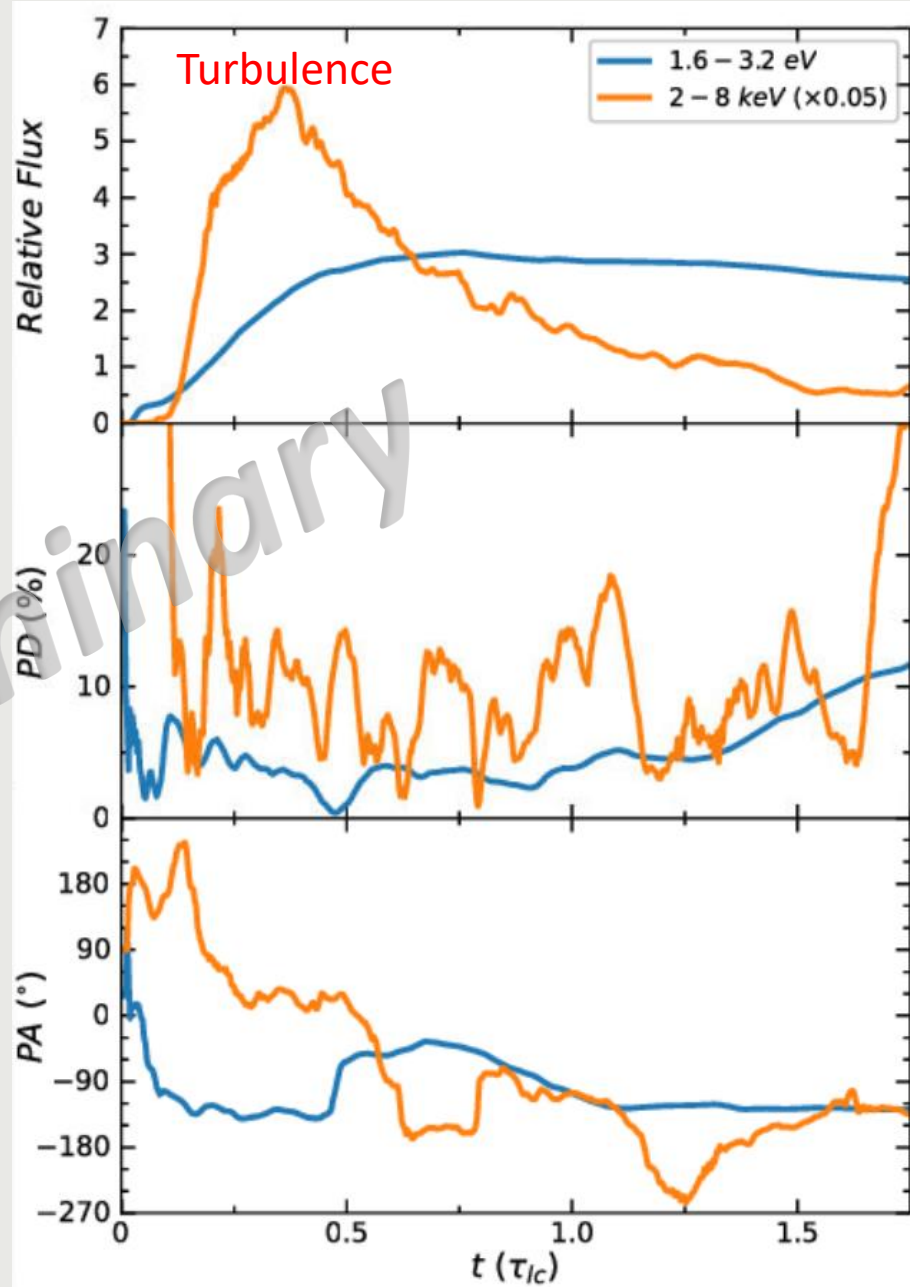
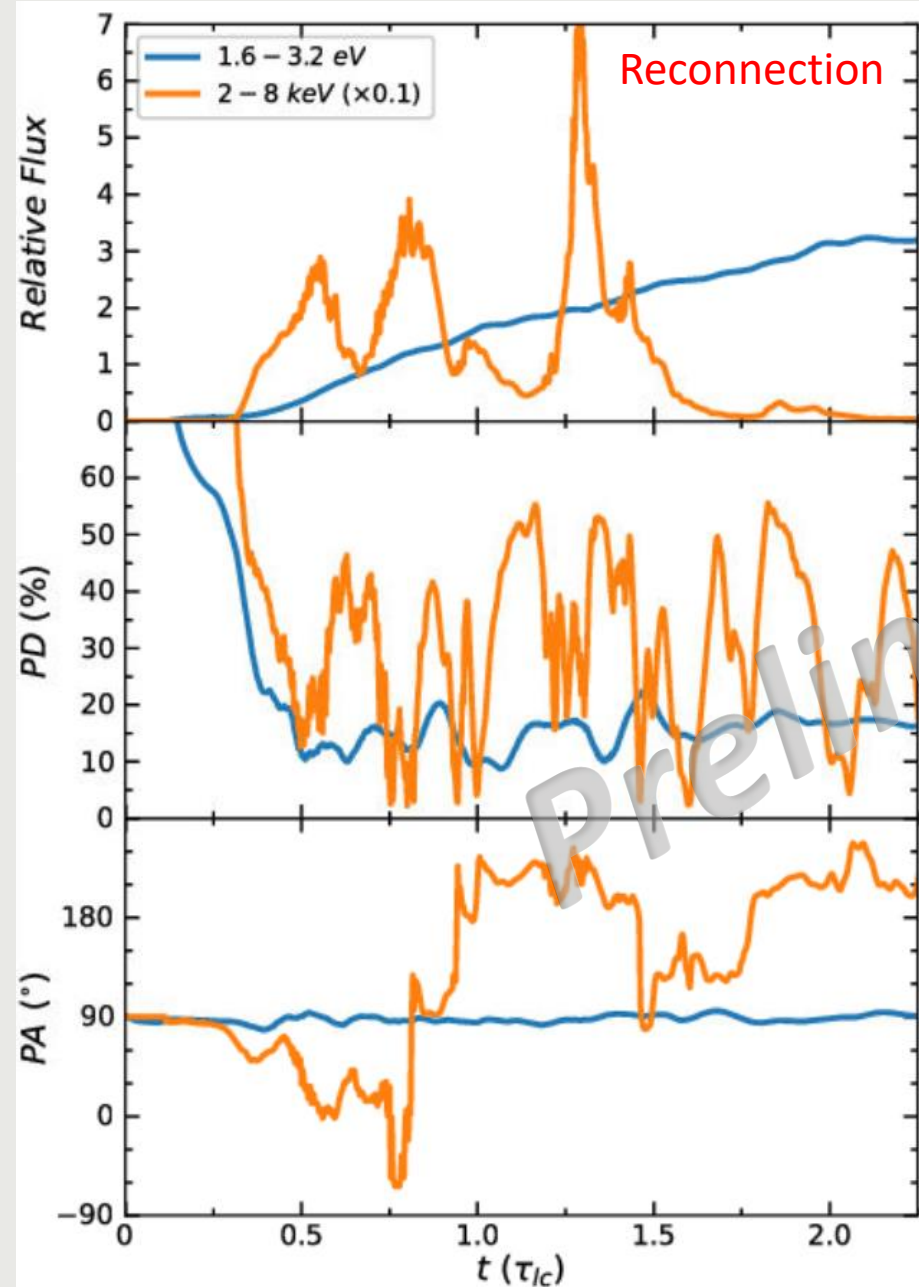
[Zhang et al. 2020 ApJ 901, 149](#)

Turbulence



1. Spectra and light curves cannot fully distinguish these mechanisms.
2. Magnetic fields (strength/shape/evolution/energetics) are distinct.
3. Optical polarization has found some clues, multi-wavelength polarimetry with IXPE can do better. (P.S. Ongoing studies on Mrk 421 and 501)

X-Ray Polarization Reveals Particle Acceleration



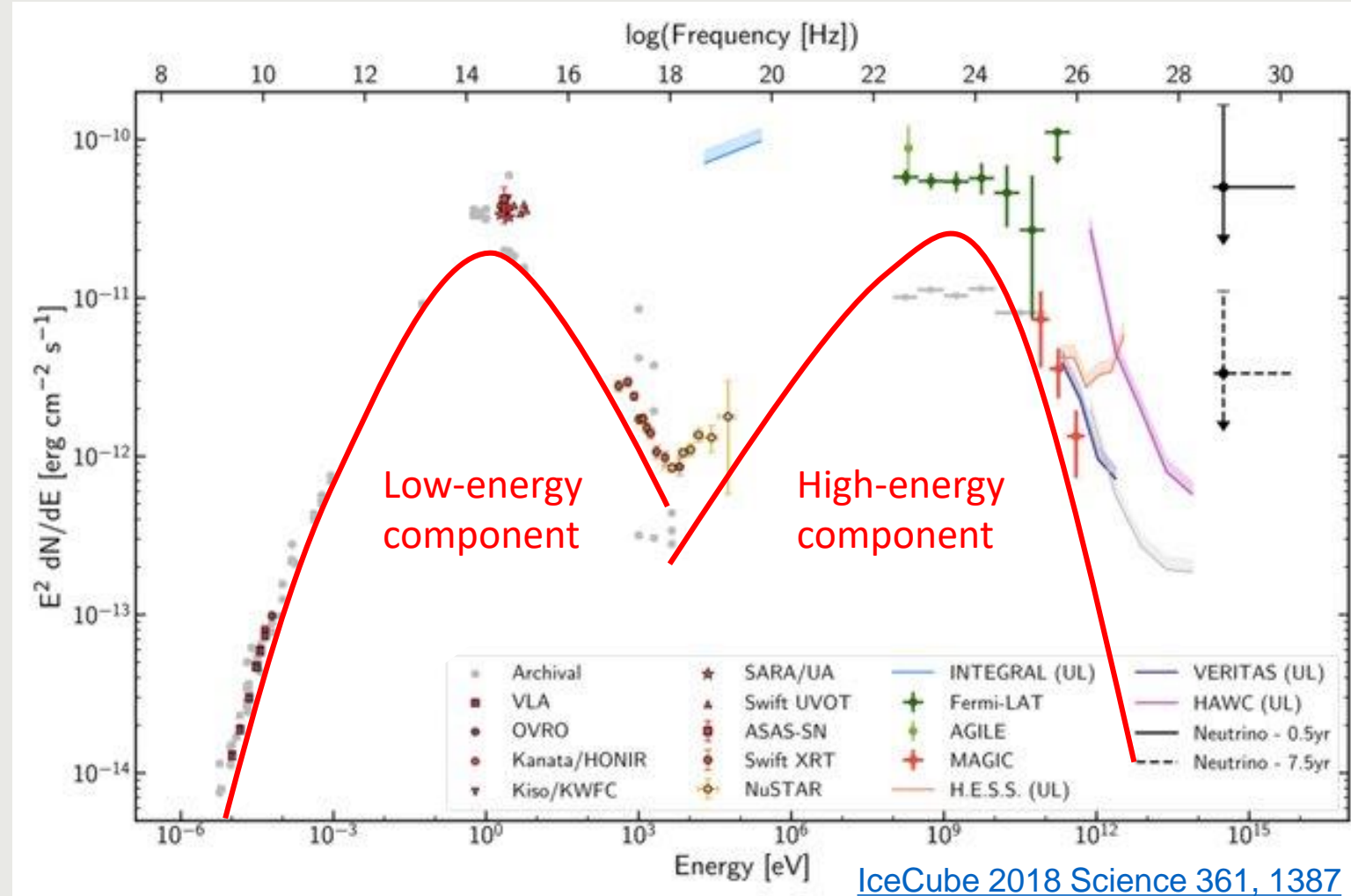
Reconnection

- ☐ Flashes of high X-ray polarization $\sim 40\text{-}50\%$
- ☐ Fast X-ray angle swings

Turbulence

- ☐ Relatively low X-ray polarization degree (10-20%)
- ☐ Angle swings not connected to flares

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All questions can be answered with multi-wavelength spectropolarimetry.
IXPE is great, COSI will be great, better polarimetry means better TDAMM.